Recent Results from the PHENIX Experiment

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for the PHENIX Collaboration

PHENIX

Introduction

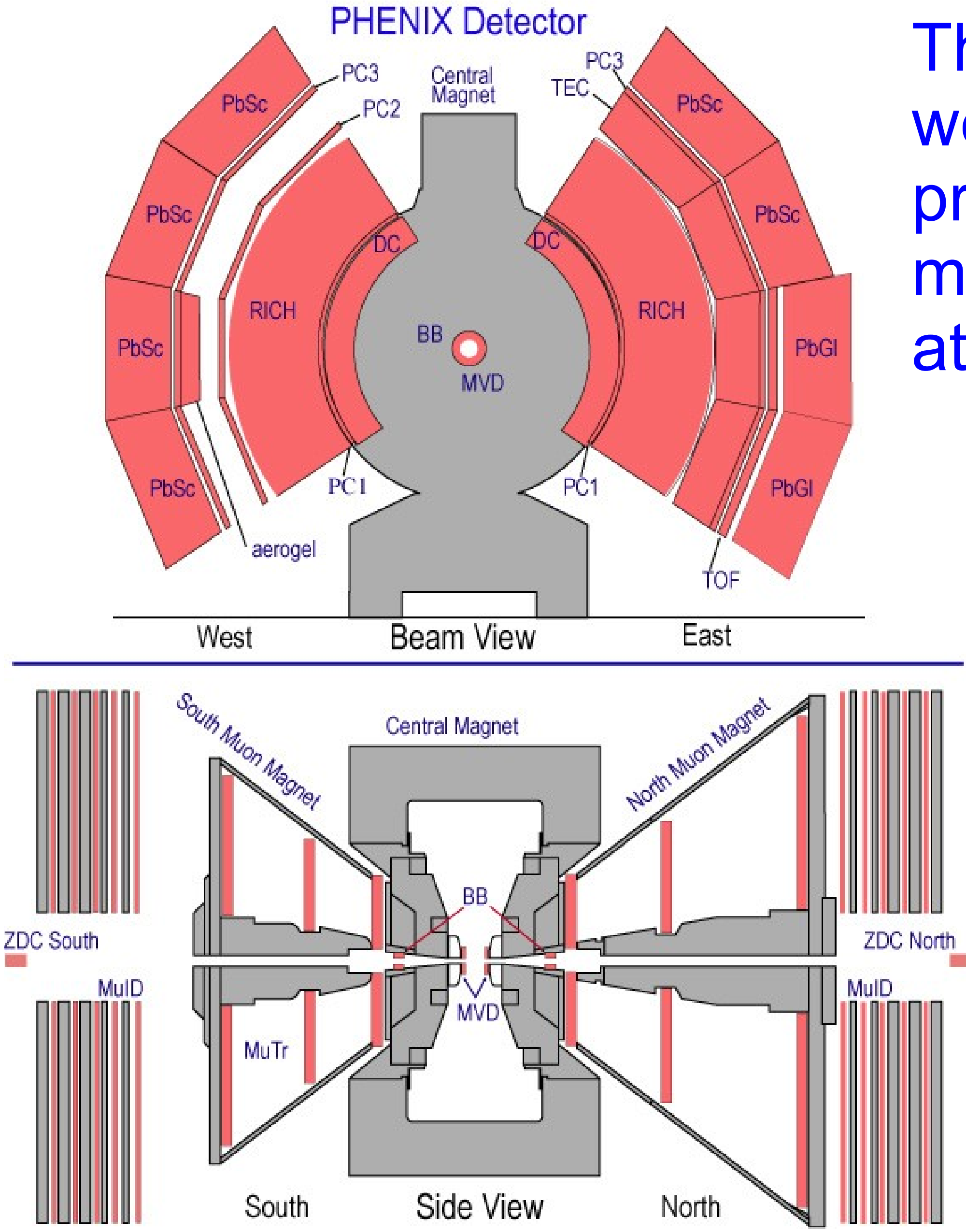
- Thermalized, hot, and dense matter is created at RHIC

- Not a gas of weakly interacting partons.

What are the properties of this matter and how do we study them?

- **Thermalized:** **collective flow**
- **Partonic:** **flow scaling with n_q**
- **Dense:** **suppresses high P_T hadrons, heavy quarks**
  modifies shape of jets
  suppresses and regenerates(?) J/ψ
- **Hot:** **direct photon production above QCD calculations**
- **Strongly coupled:** **heavy quarks flow**

The PHENIX Detector



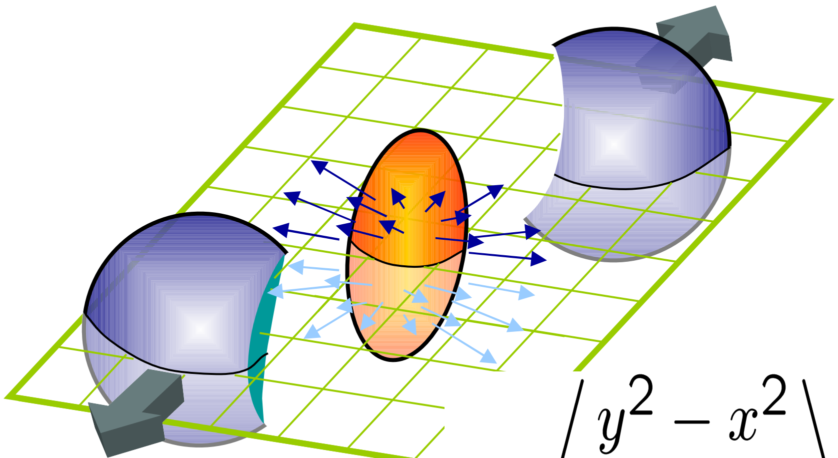
The PHENIX Experiment is well suited for measuring the properties of hot and dense matter created in NN collisions at RHIC

- identified hadrons
- photons and neutral mesons
- leptons (e and μ)
- acceptance is large enough extract information about collective flow and jets
- triggers for rare processes

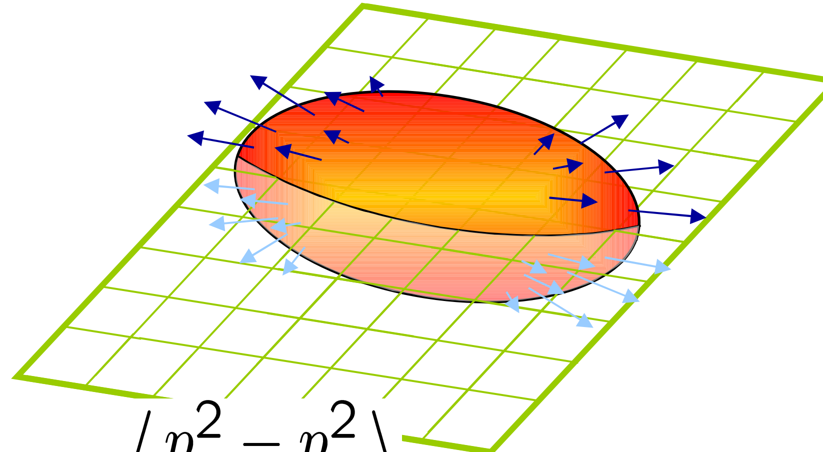
The system is THERMALIZED:

COLLECTIVE FLOW

Flow at RHIC - Introduction



$$\epsilon = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$



$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

spatial anisotropy ⇨ properties of the matter ⇨ **momentum anisotropy**

Elliptic flow = v_2 = 2nd Fourier coefficient of momentum anisotropy:

$$dn/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\,\phi) + \ldots$$

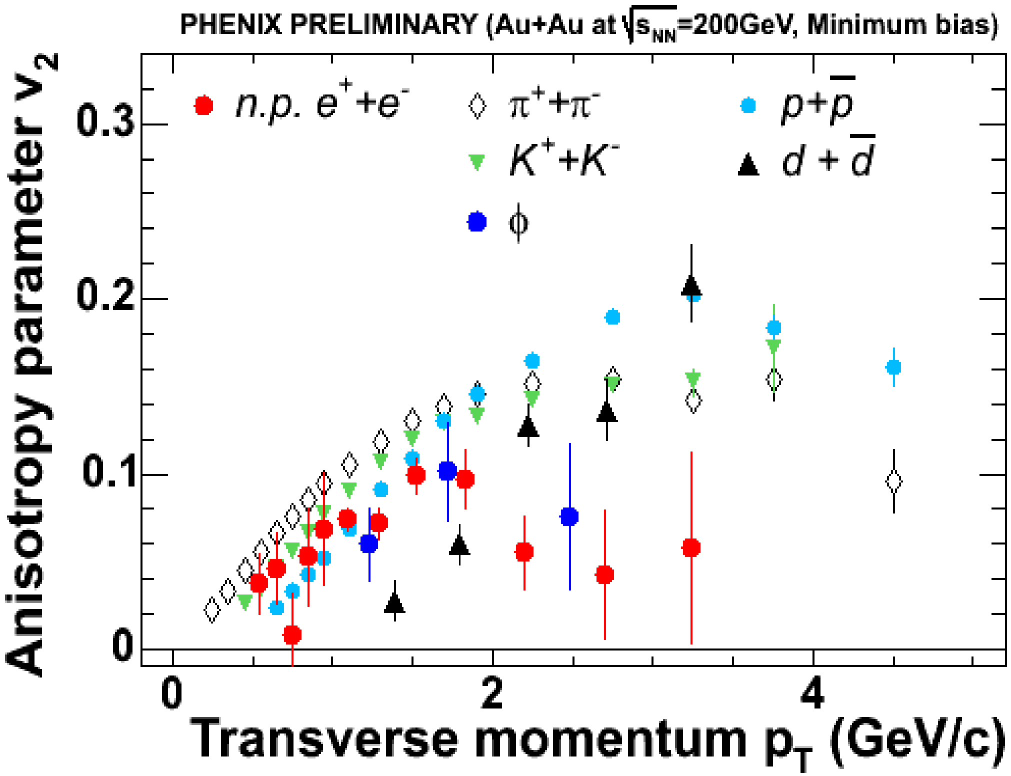
Spatial anisotropy lost if system is not thermalized early.

Ideal fluid dynamics: v_2 scales with eccentricity; v_2/ε independent of system size; v_2 increases with c_s.

See talk by Akitomo Enokizono

Flow – the results

Significant elliptic flow observed for all identified particles

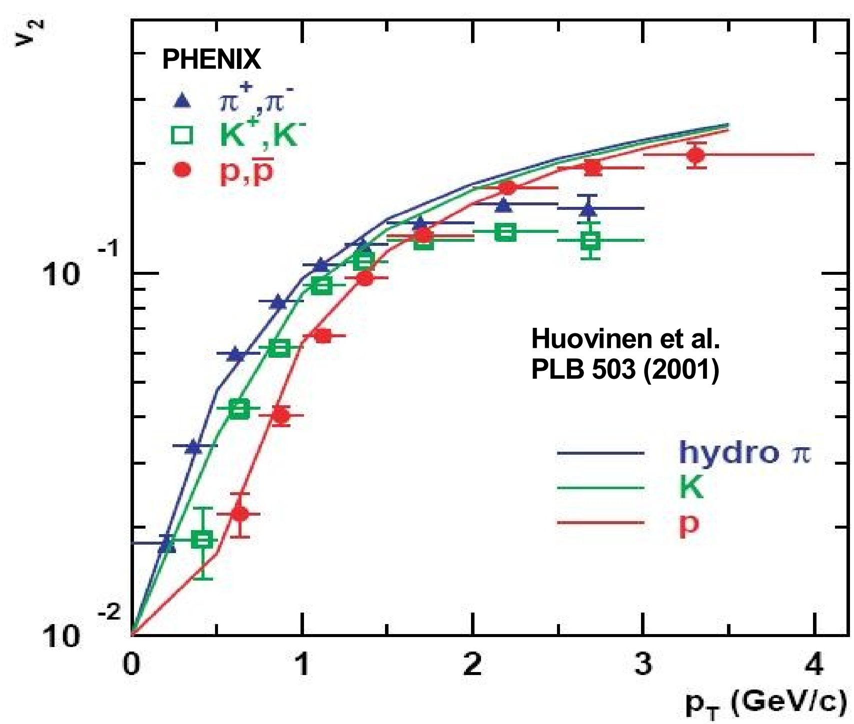


Implies strongly coupled thermalized medium

Hydrodynamic calculations with zero viscosity and early thermalization agree with data

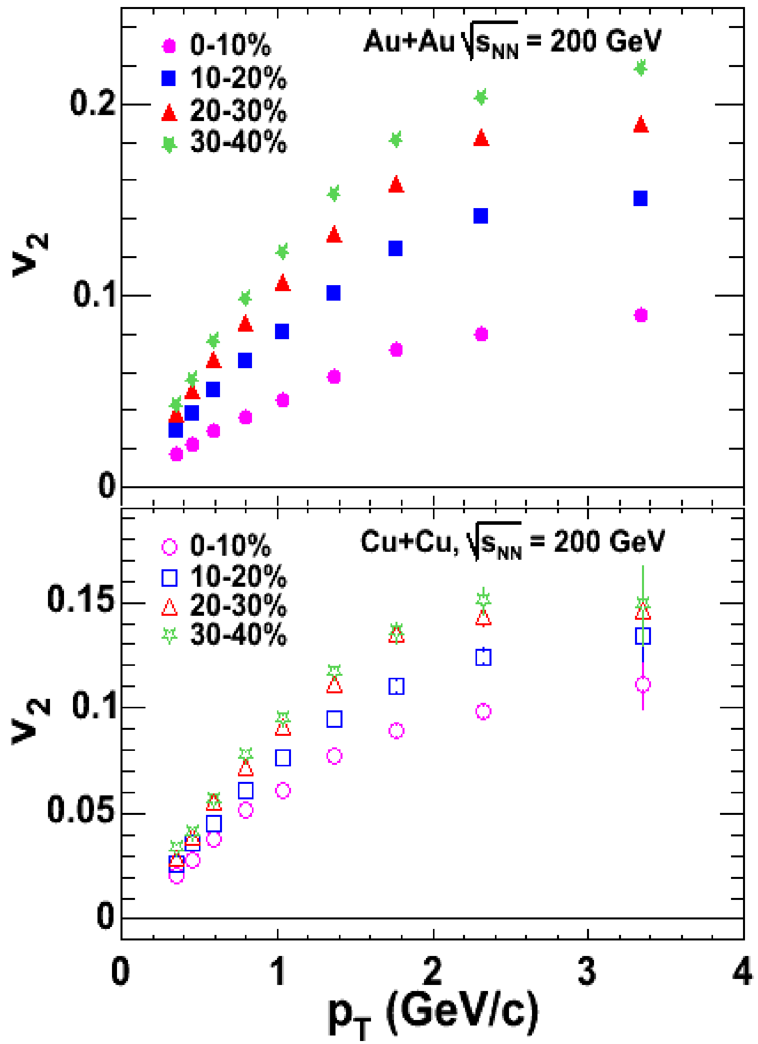
$\tau_{therm} \sim 0.6 - 1.0$ fm/c

$\varepsilon \sim 15\text{-}25$ GeV/fm^3

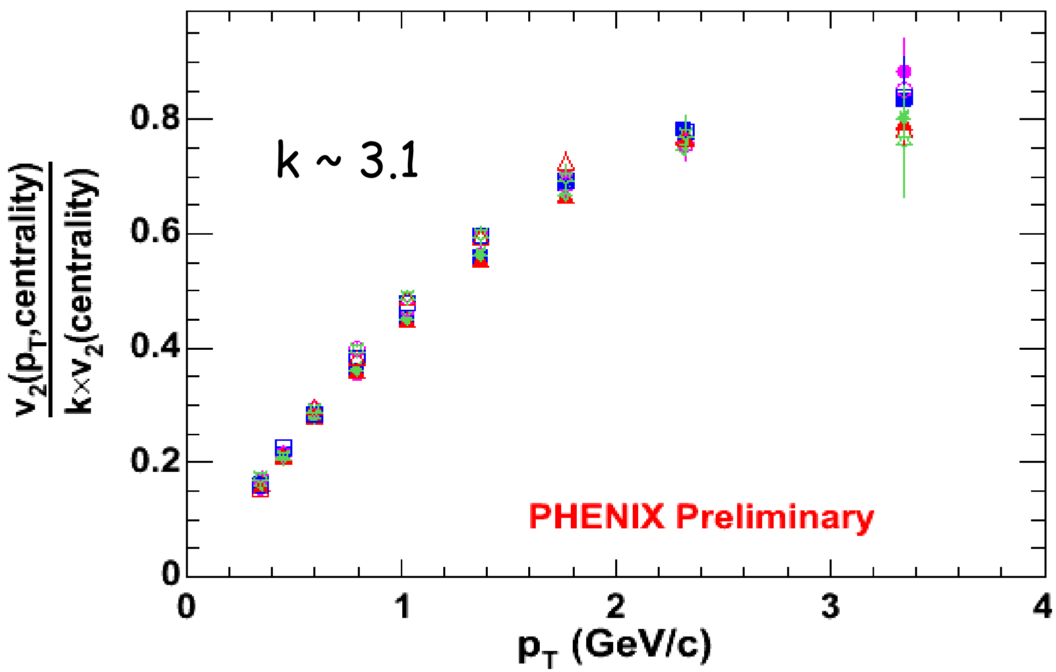


Flow – eccentricity and system size scaling

Do you see a scaling?
Divide by eccentricity.



Calculate eccentricity
from Glauber model
OR
Use integrated (over P_T) v_2 since
it is proportional to eccentricity

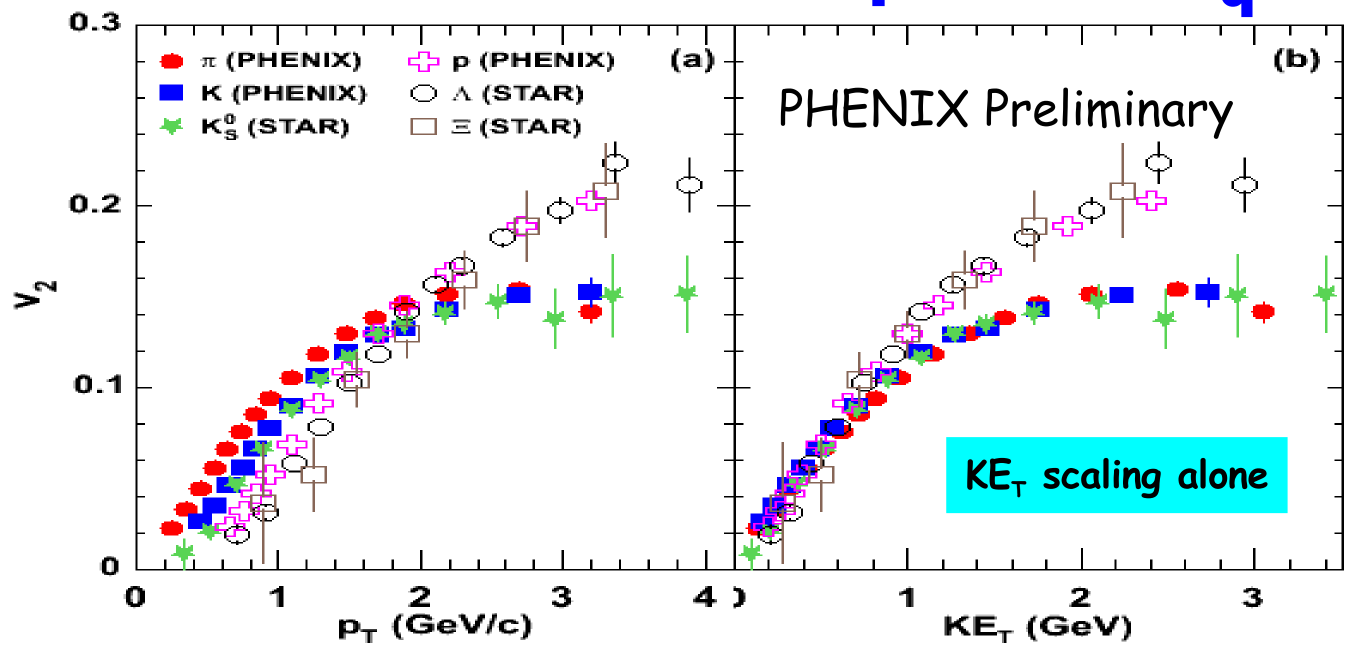


v_2 scales with eccentricity and system size: indicates high degree of thermalization

The system is PARTONIC:

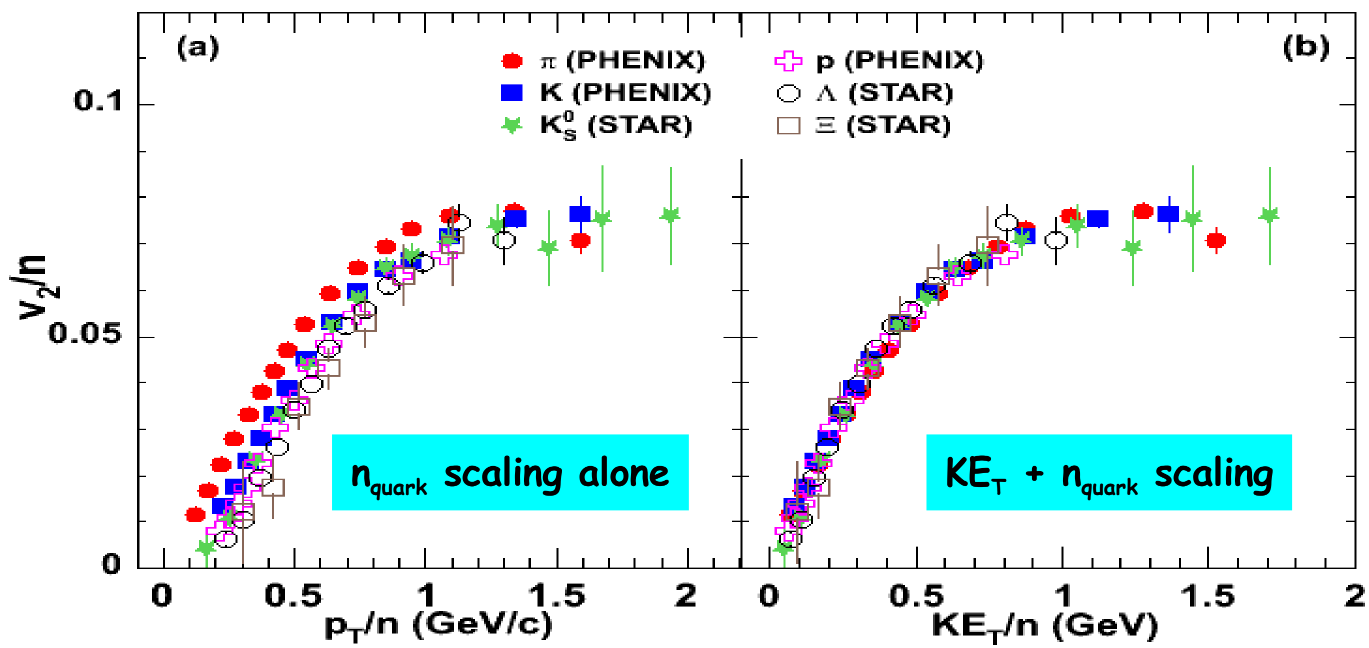
COLLECTIVE FLOW

Flow: KE_T and n_q scaling



$KE_T = m_T - m_0$

transverse kinetic energy of a particle in relativistic fluid



KE_T scaling:

Hydrodynamic behavior

n_q scaling:

Evidence for partonic flow

The system is DENSE:

HIGH P_T SPECTRA SUPPRESSION

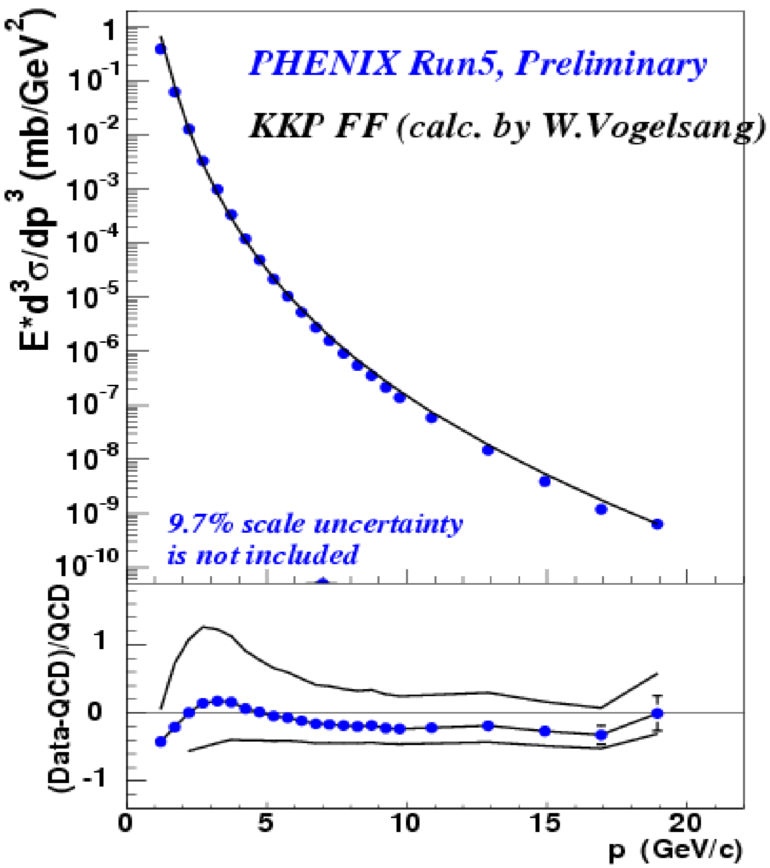
High P_T suppression - introduction

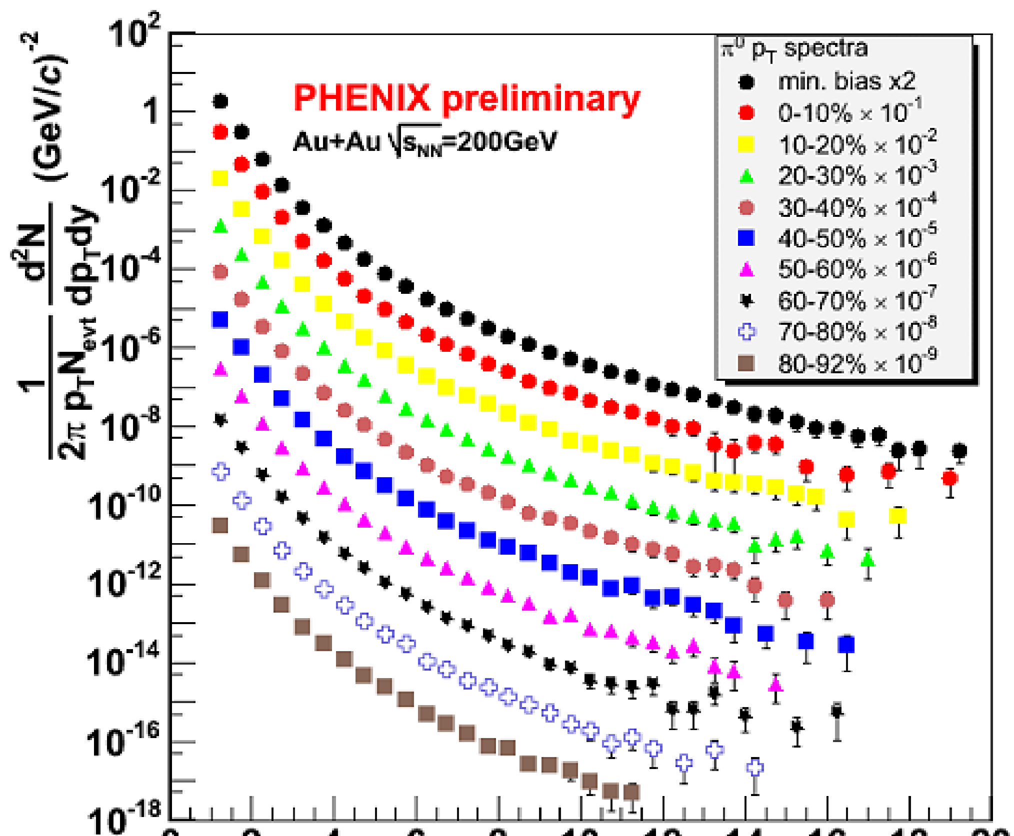
High P_T particles:

- created early by hard scatterings
- sensitive to the entire lifetime of the system
- "calibrated" by pQCD
- interact with medium via the strong force

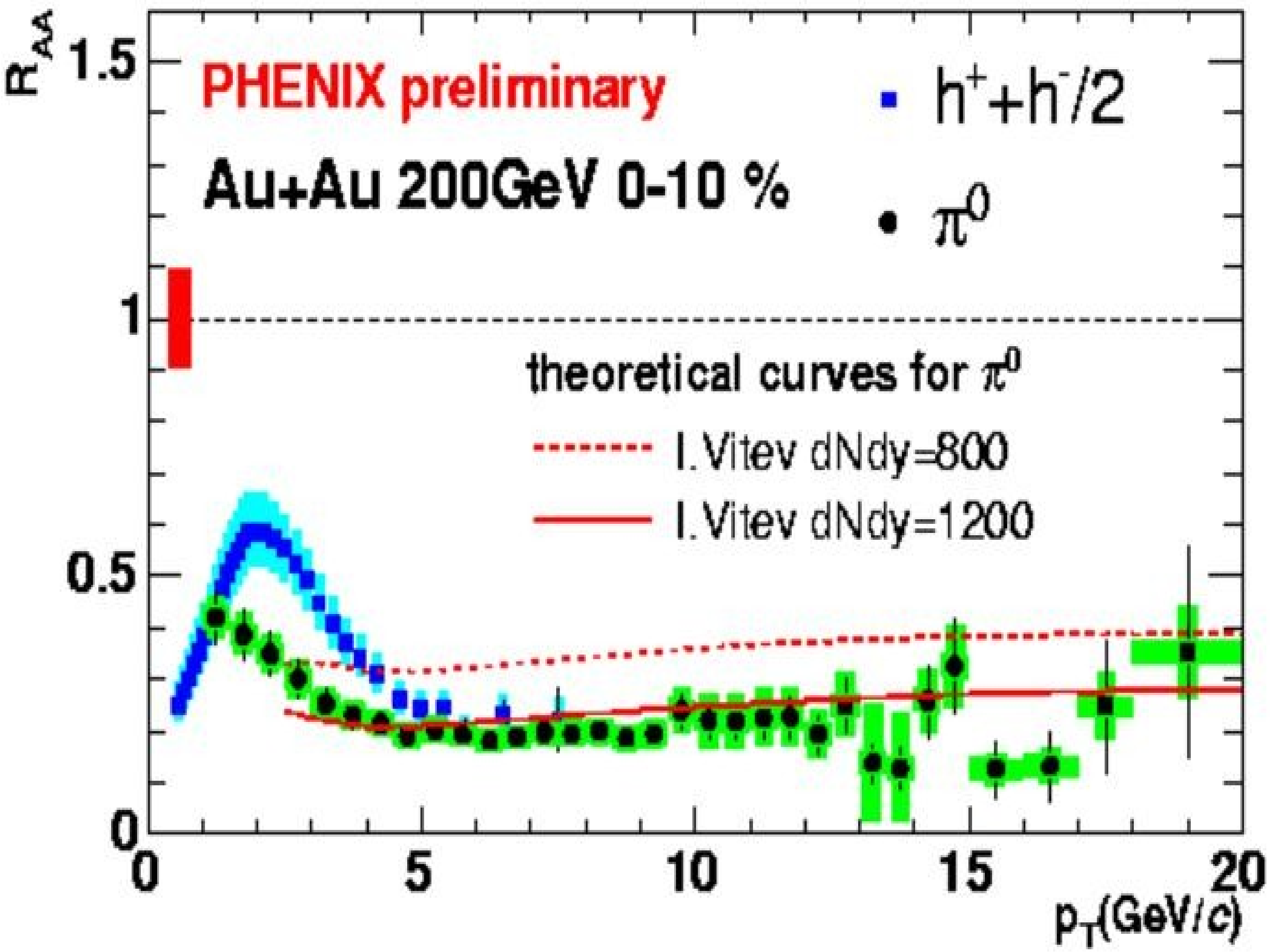
Nuclear modification factor:

$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{T_{AA} \cdot \left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$





High P_T suppression in AuAu

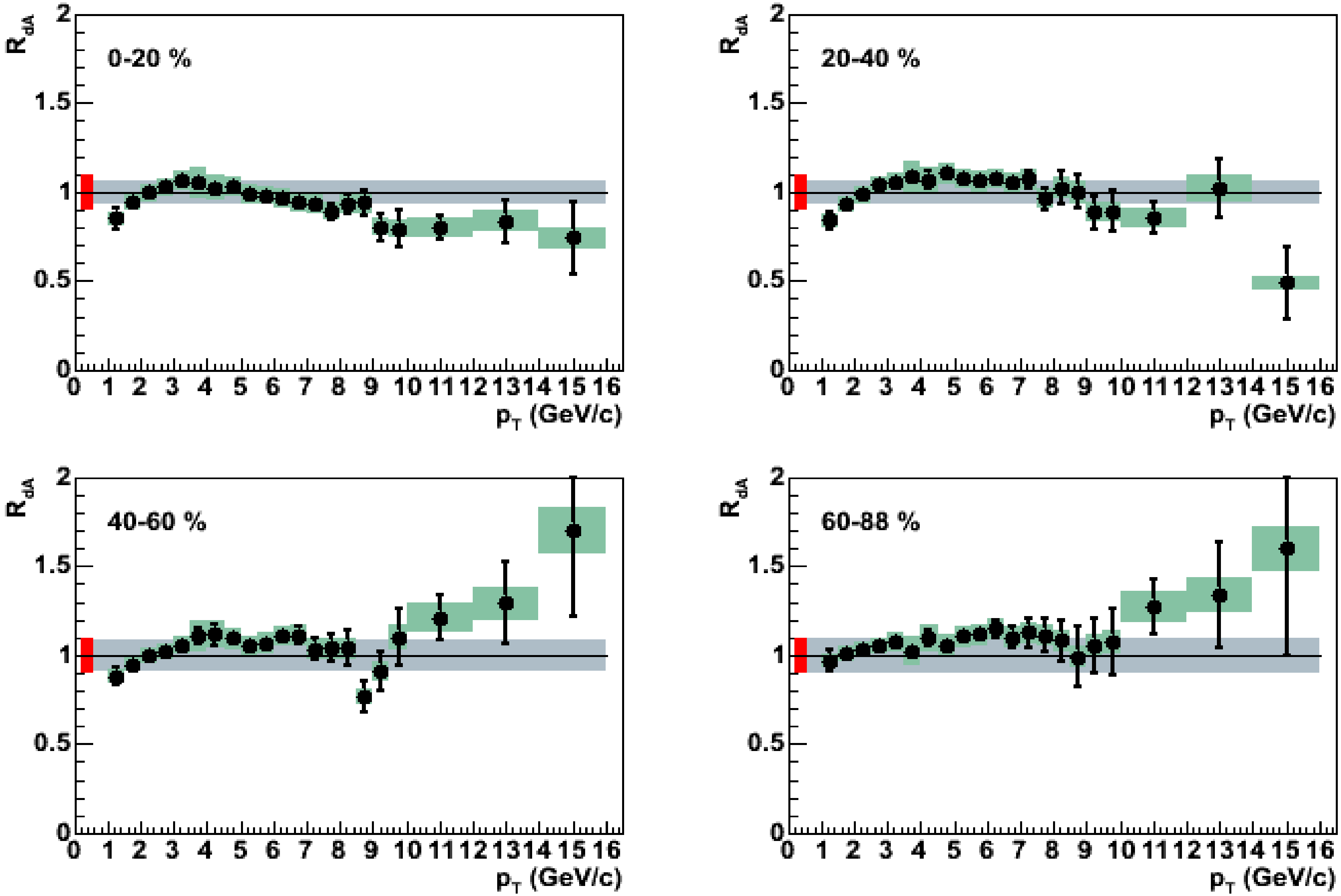


Suppression is very strong and flat up to 20 GeV/c

Consistent with gluon density in the matter dN/dy=1200

Matter is so opaque that even 20 GeV/c π^0 are strongly suppressed

Control experiment: dAu

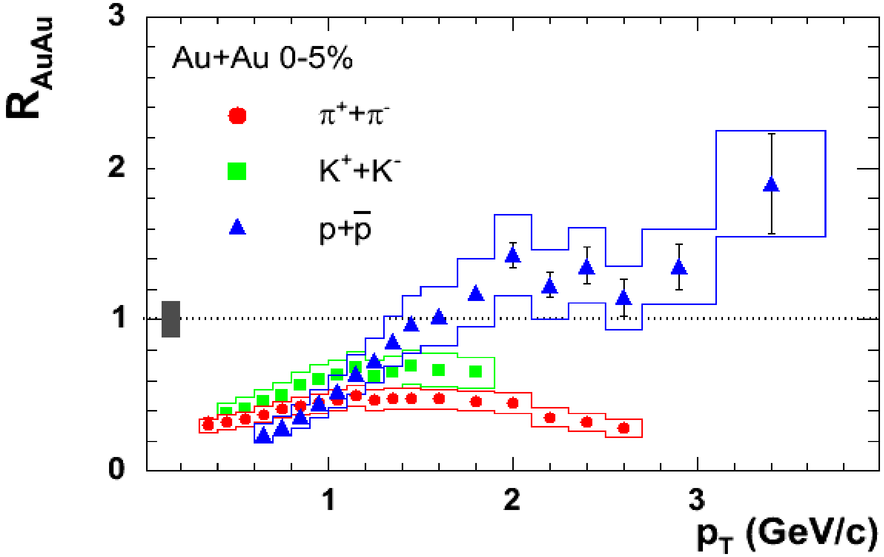


No significant initial state effects in dAu

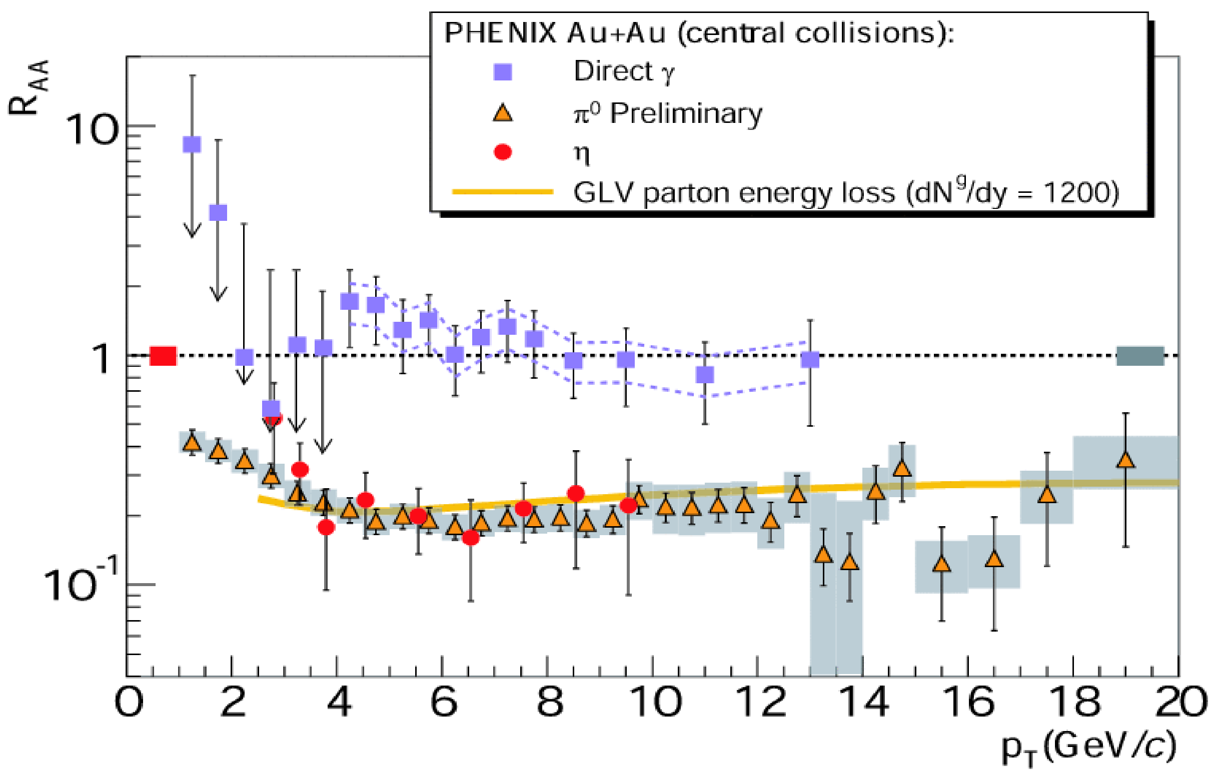
The system is PARTONIC:

HIGH P_T SPECTRA SUPPRESSION

Suppression for mesons and baryons



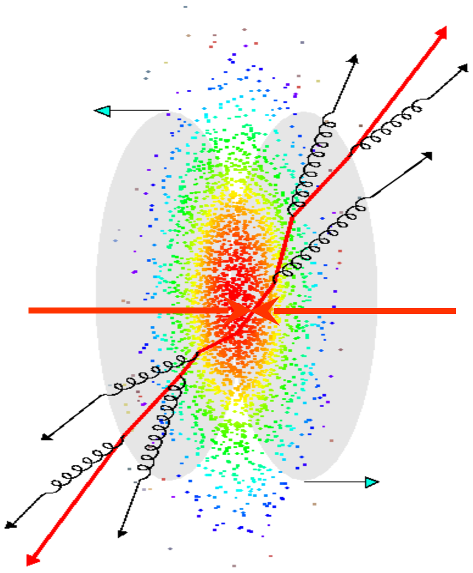
Common suppression for π^0 and η but protons are different: suppression at partonic level



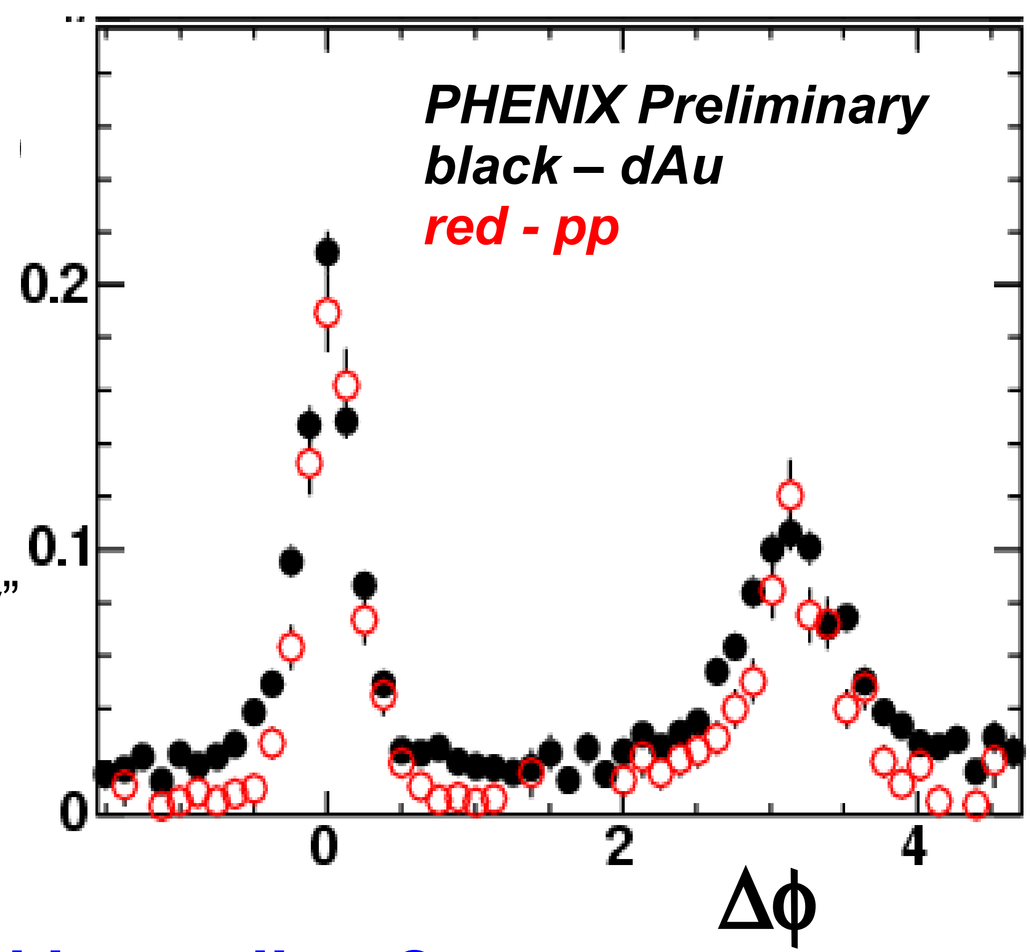
Jet Correlations

Another way to look at the same processes

Dijet event in a hot QCD medium



Baseline measurement in pp and dAu:



Trigger on one leading hadron, and look for associated particles, “near” and “away”

- correct for non-uniform PHENIX acceptance
- jets are identified statistically
- model independent

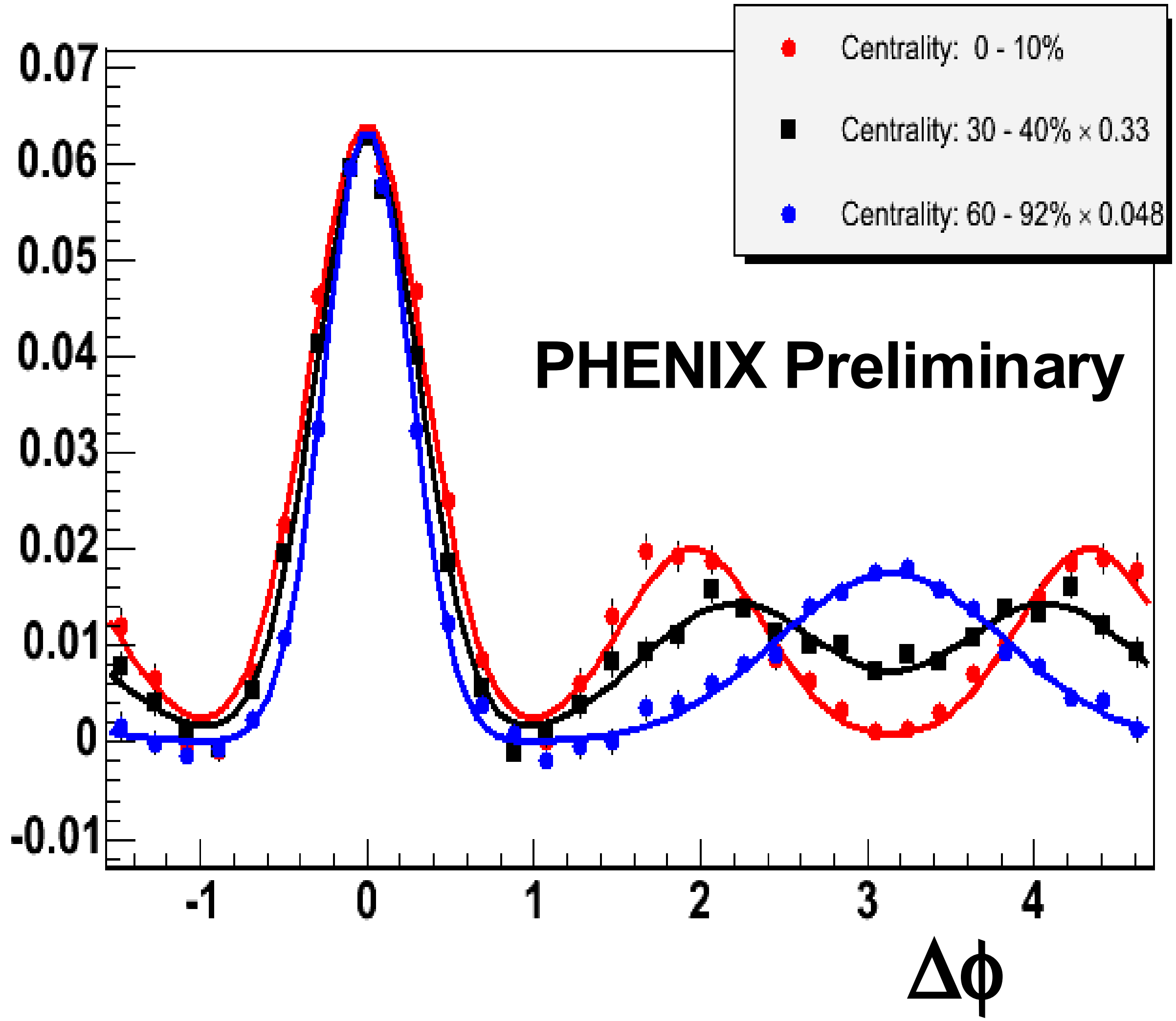
Are jets modified in medium?

Jet modification in AuAu

Yes!

Away-side jet is broadened and split in central and mid-central collisions (Mach cone? Cherenkov radiation?

Can we measure medium properties from the shape? (sound velocity or dielectric constant)



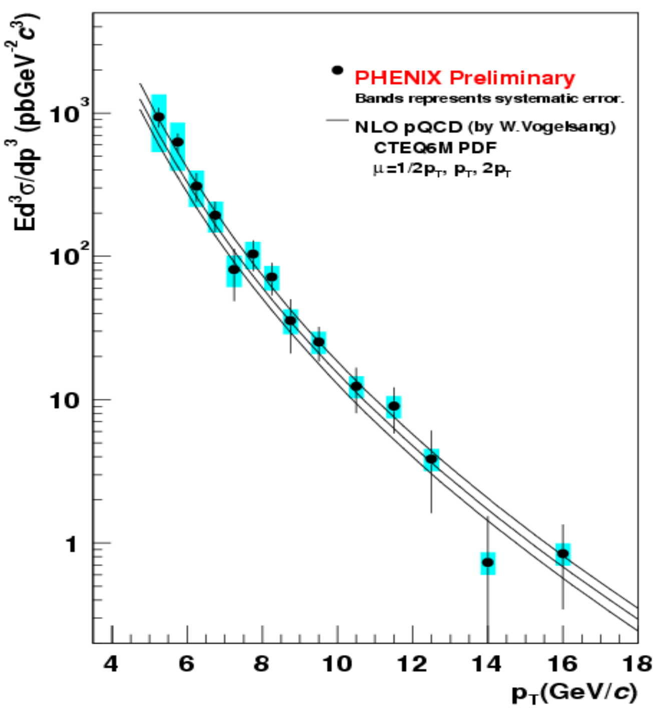
The system is HOT:

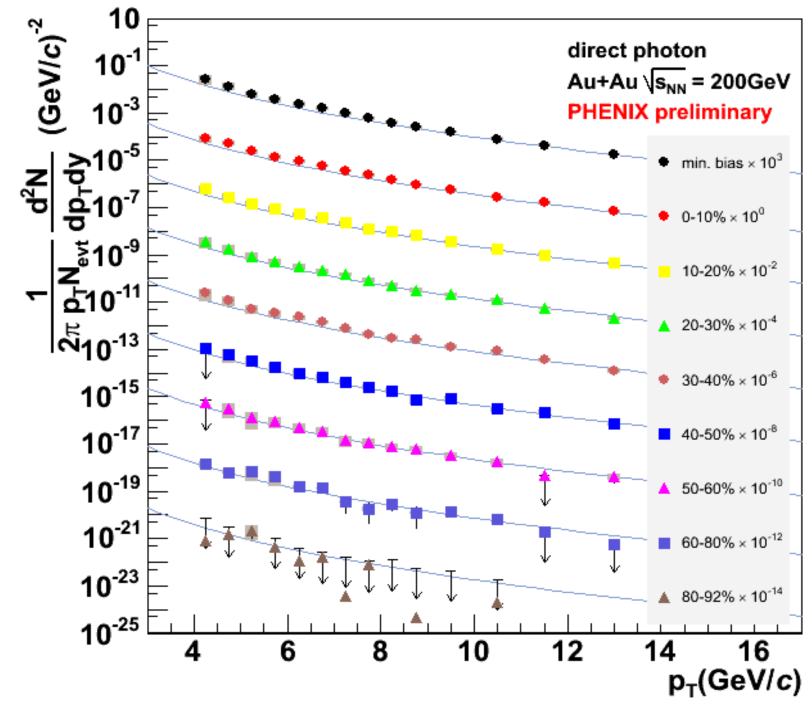
DIRECT PHOTONS

Direct Photons

Thermometer of the plasma (thermal radiation from QGP?)
Penetrating probe: does not interact strongly
In AuAu measurement is simplified by the hadron suppression

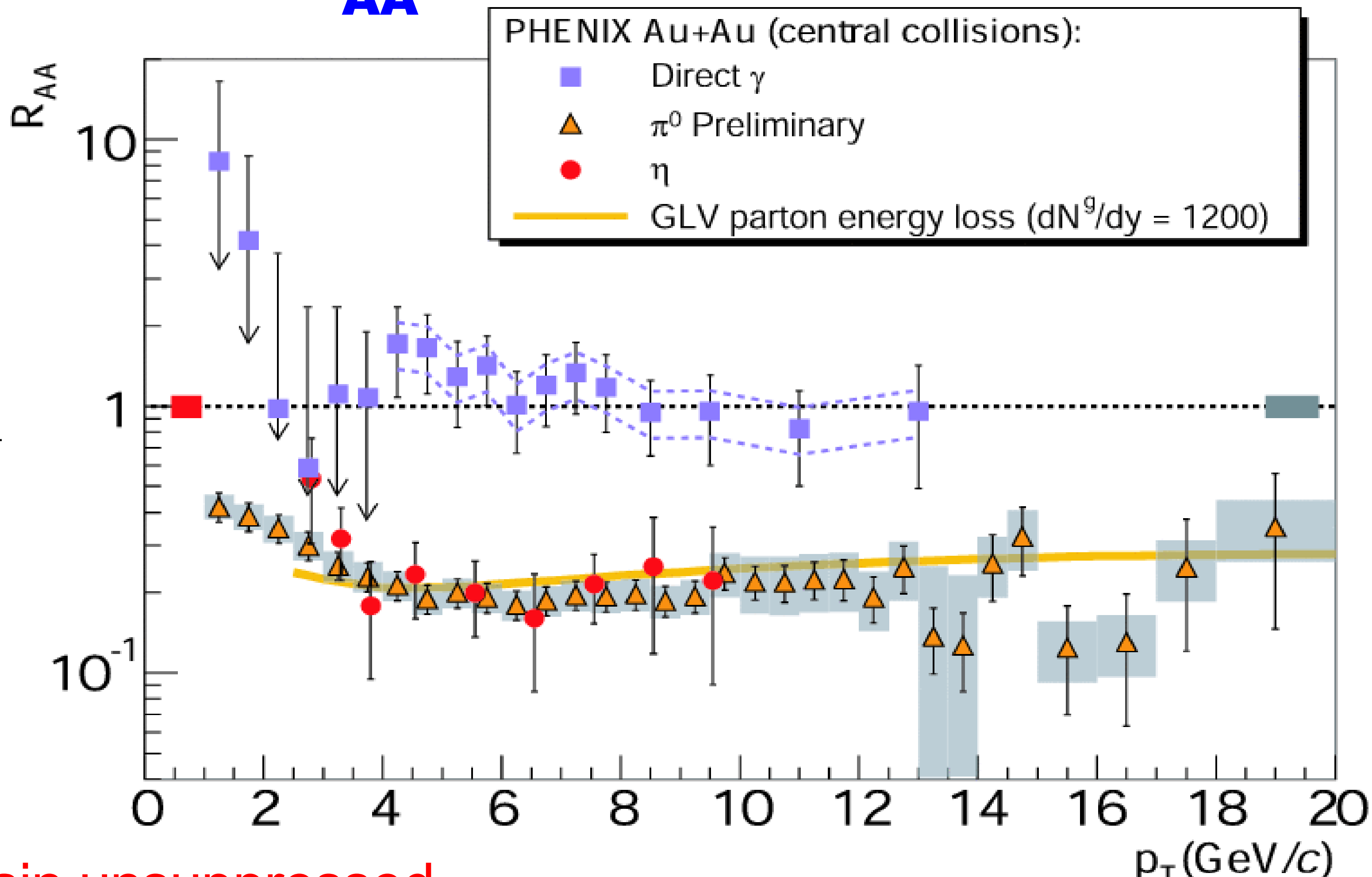
PHENIX has measured direct photons in pp, dAu and AuAu
- pp: good agreement with pQCD calculations
- dAu: no indication of initial state effects
- AuAu: what can we learn from direct photons?
  - at high P_T consistent with N_{COLL} scaled pQCD





Direct Photon R_{AA}

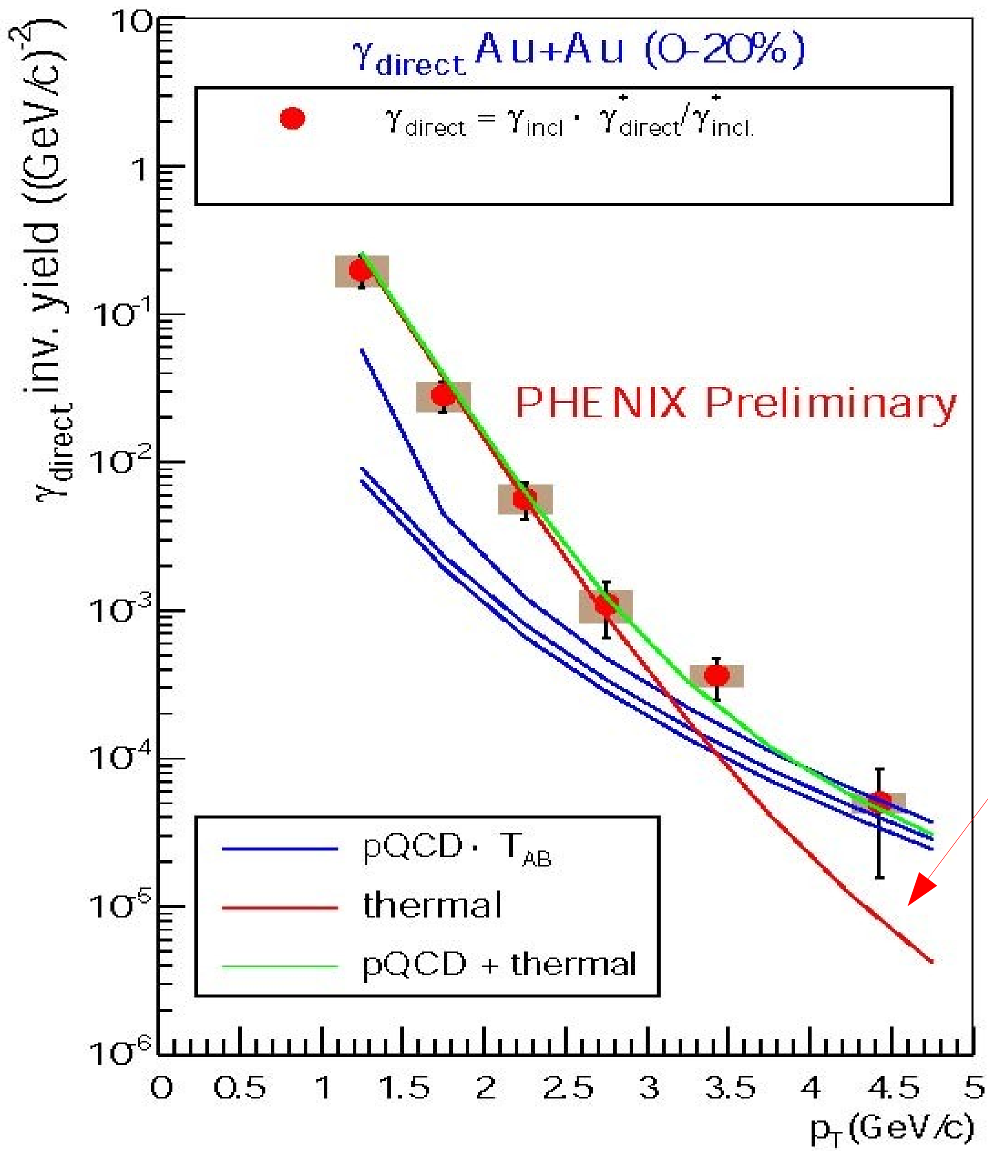
$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{T_{AA}\cdot\left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$



Photons remain unsuppressed
Hadron suppression is not an initial state effect
Direct photons are well understood at high P_T (pQCD)

Can we find indications of thermal radiation at lower P_T?

Thermal Photons?



The first promising result of direct photon measurement at low P_T from conversion pair analysis

The rate is above pQCD:
D. d'Enterria, D. Peressounko
nucl-th/0503054

If these photons are indeed thermal, they can provide the first direct measurement of initial temperature of the matter:

T_0 = 590 MeV

τ_0 = 0.15 fm/c

The system is

DENSE

and

STRONGLY COUPLED:

HEAVY QUARKS

Heavy Quarks

- Created during initial hard scattering
- Yield is insensitive to final state effects
- Sensitive to initial state temperature and gluon density
- Quarkonium suppression – QGP signature

Two ways to study heavy quark production in PHENIX:

- open charm: single electrons and muons (indirect measurement)
    - subtraction of "photonic" electrons (mid-rapidity)
        - converter method as a crosscheck
    - single muons (forward and backward rapidity)
        - subtract: muons from decays, punch-through and stopped hadrons

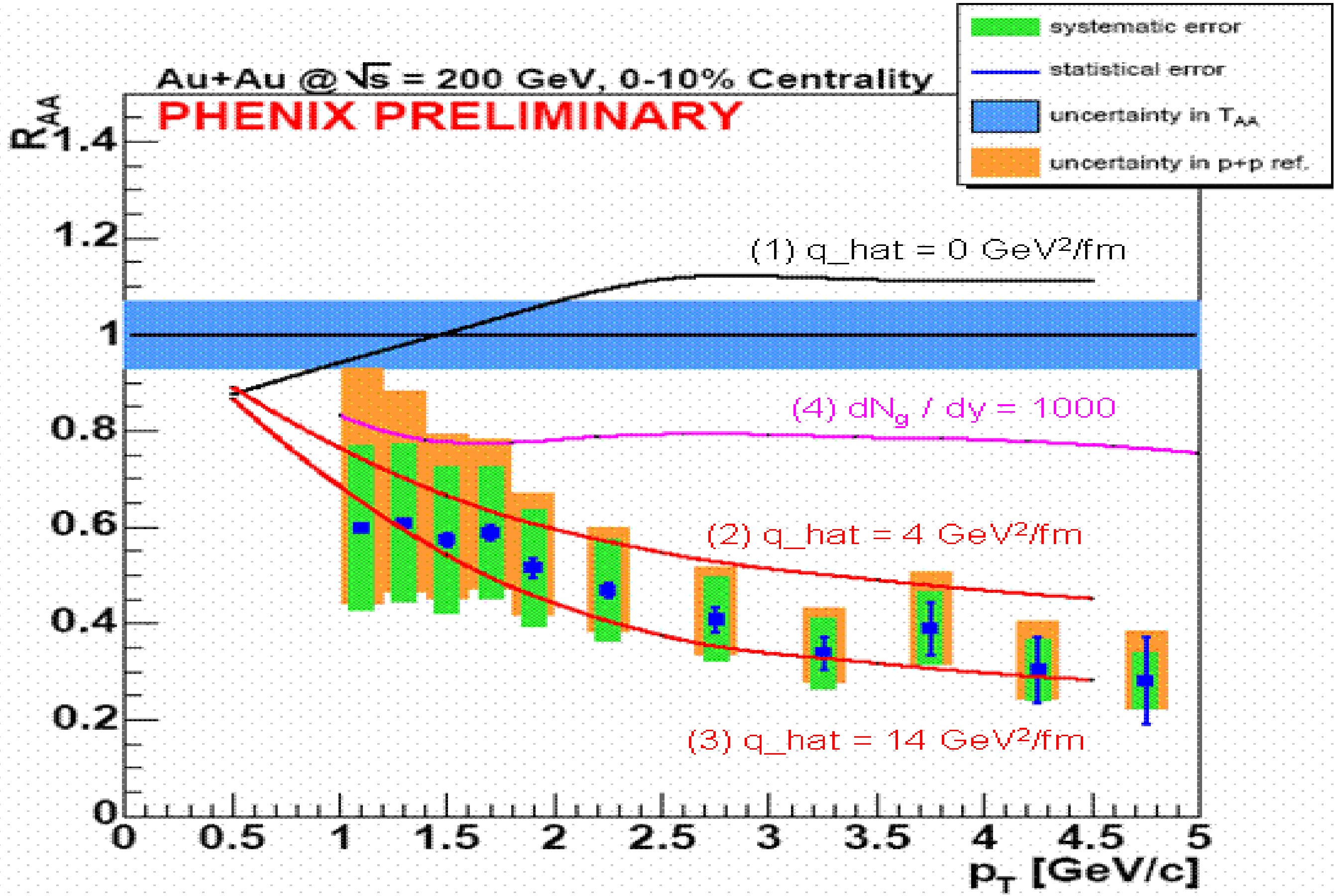
- quarkonium: J/ψ in dielectron and dimuon channels
    - J/ψ are measured via di-lepton invariant mass, combinatorial background subtracted.

See talk by Cesar Luis da Silva

Heavy Quarks Energy Loss

Open charm is measured indirectly:

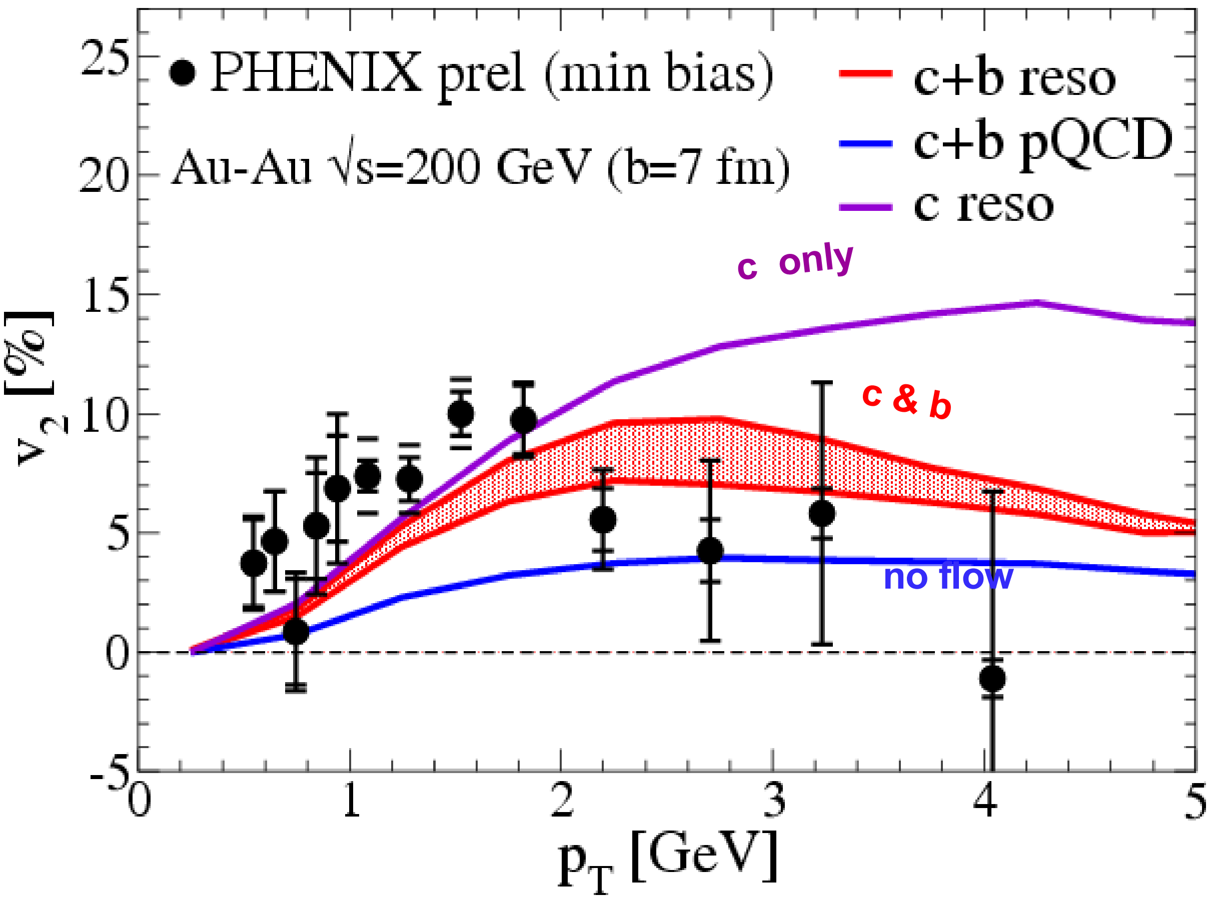
- measure all electrons
- subtract electron spectra expected from Dalitz decays of mesons and from conversions
- converter method as a crosscheck



Theory curves:
(1-3) from N. Armesto, *et al.*, PRD 71, 054027
(4) from M. Djordjevic, M. Gyullasy, S.Wicks, PRL 94, 112301

- The data suggest large charm-medium cross section
- Matter is so dense and strongly coupled that even heavy quarks are suppressed

Heavy Quarks Flow



Charm flows, but flow is not so strong as for light mesons

Drop of the flow strength at high p_T: b contribution?

Theory curves above for HQ resonance rescattering:
Van Hees, Greco, Rapp, Phys. Rev. C73:034913

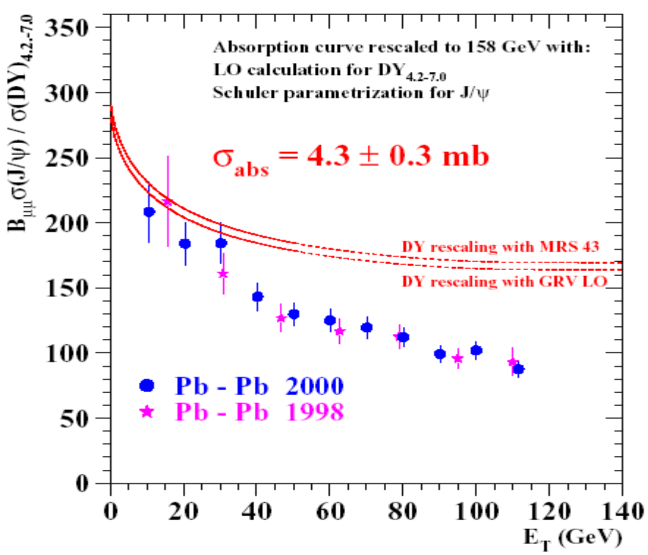
The matter is so strongly coupled, that even heavy quarks flow

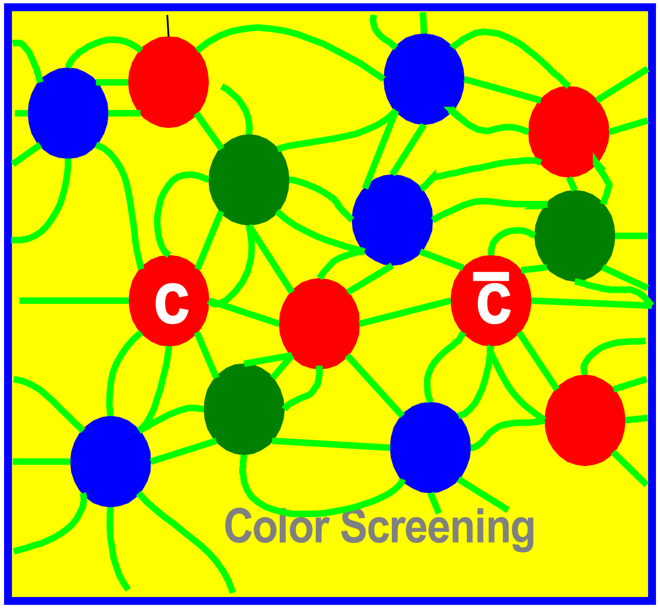
Flow of J/Psi?

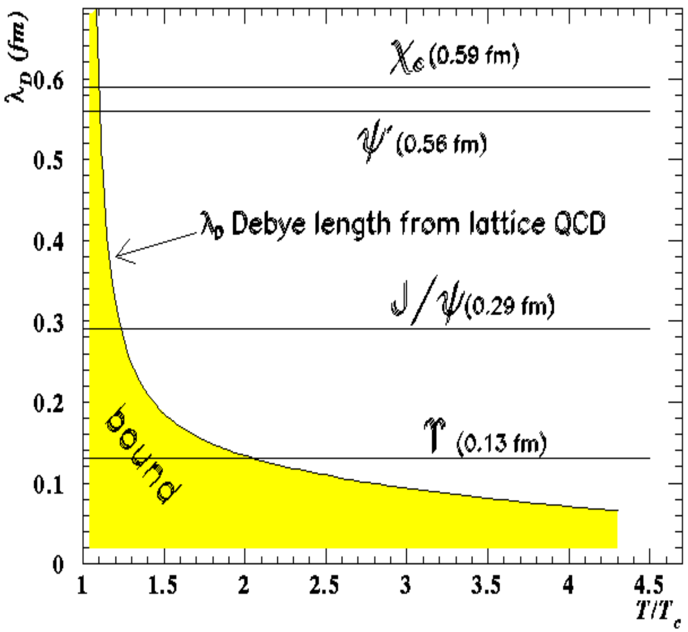
J/ψ suppression at RHIC

Debye screening predicted to destroy J/ψ's in a QGP
- Recombination (coalescence) can compensate for screening?
- J/ψ not screened at all? Suppression due to less feed-down from melted higher resonances?

NA50 anomalous suppression







Recent lattice caculations predict even higher meling temperature for J/ψ (>2T$_C$)

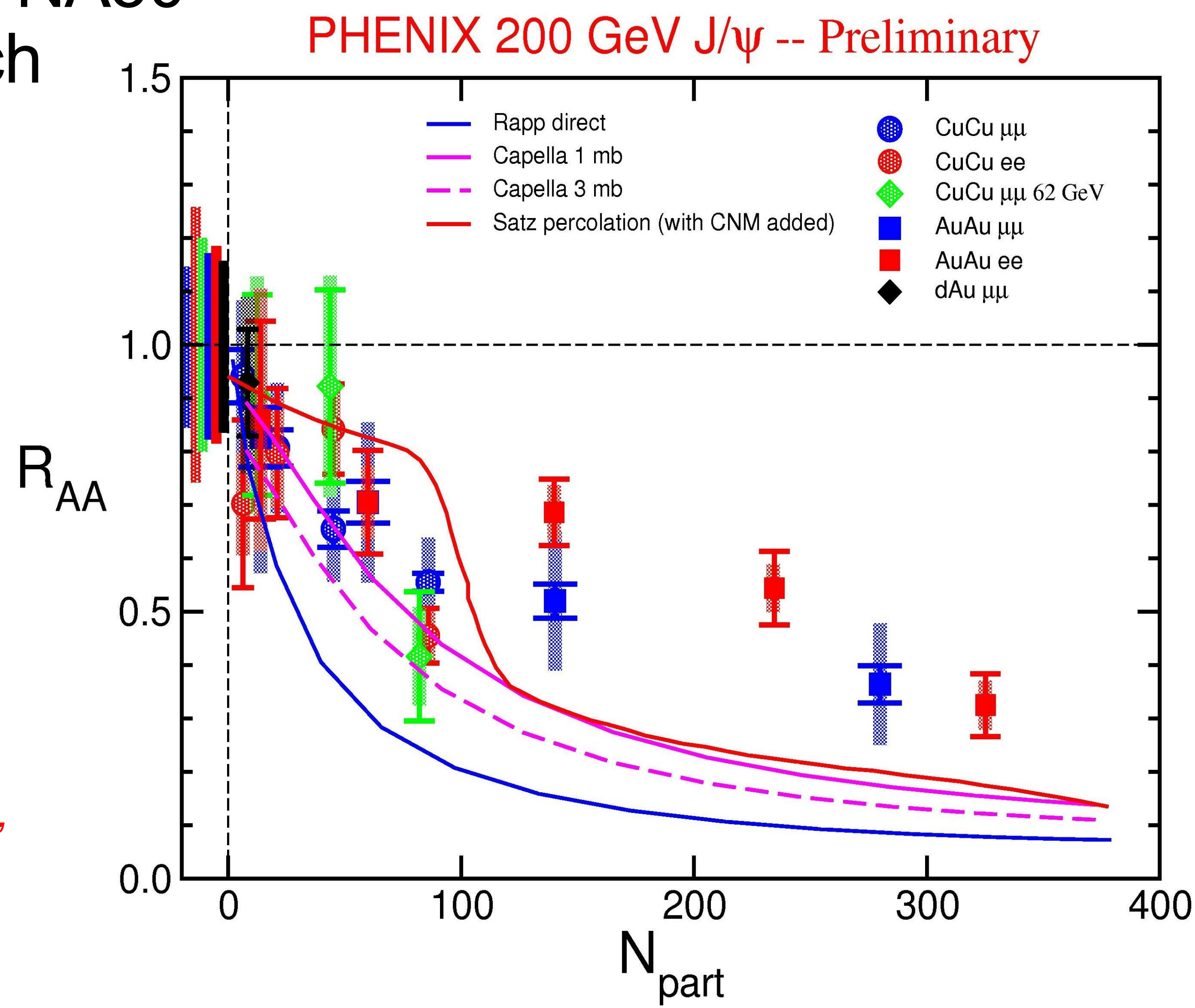
J/ψ suppression at RHIC – the results

Models that reproduce NA50 results predict too much suppression at RHIC

Rapp: direct production with CNM effects, no regeneration.
Grandchamp, Rapp, Brown hep-ph/0306077

Capella: comovers with normal absorption shadowing.
Capella, Ferreiro, hep-ph/0505032

Satz: color screening in QGP with CNM added. *Digal, Fortunato, Satz, hep-ph/031354*

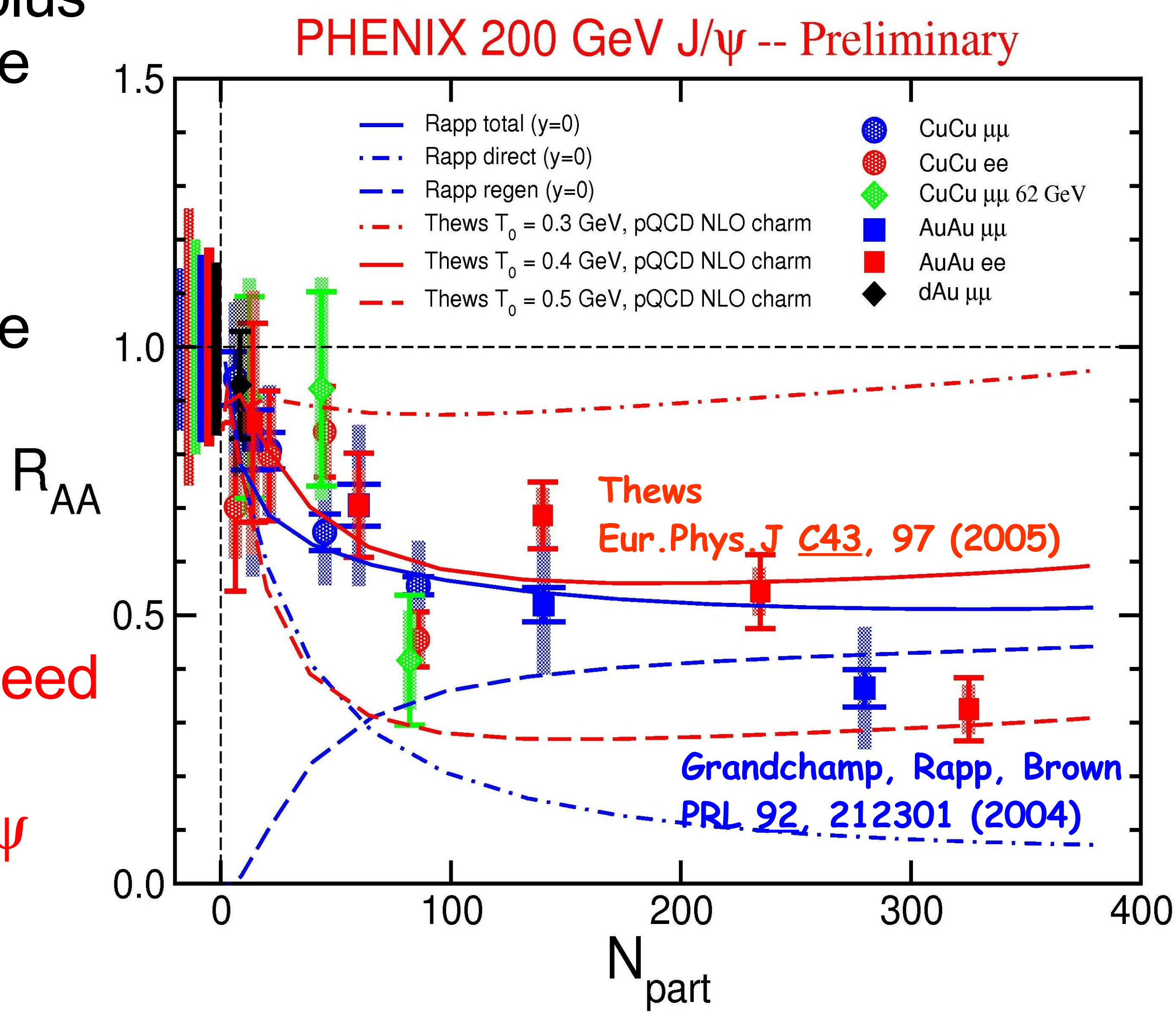


J/ψ suppression
models with recombination/coalescence

Models with suppression plus recombination/coalescence work much better!

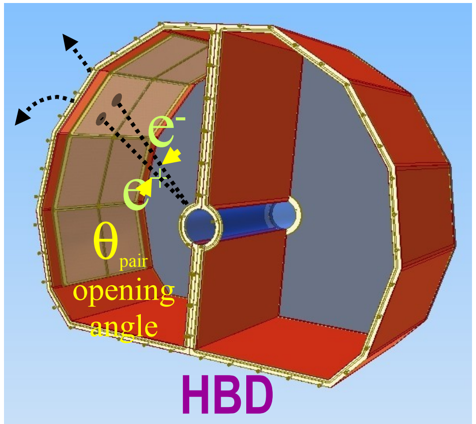
Alternative explanations: Sequential screening of the higher mass resonanses down to J/ψ

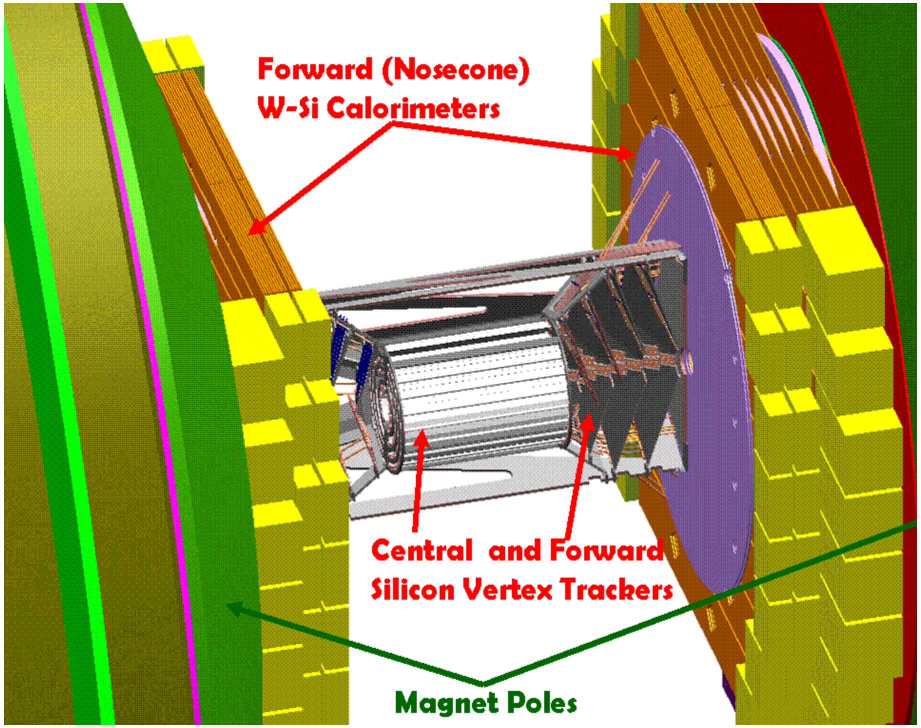
To understand J/ψ suppression at RHIC we need more charmonium measurements. ψ', χ_C, J/ψ polarization, flow...

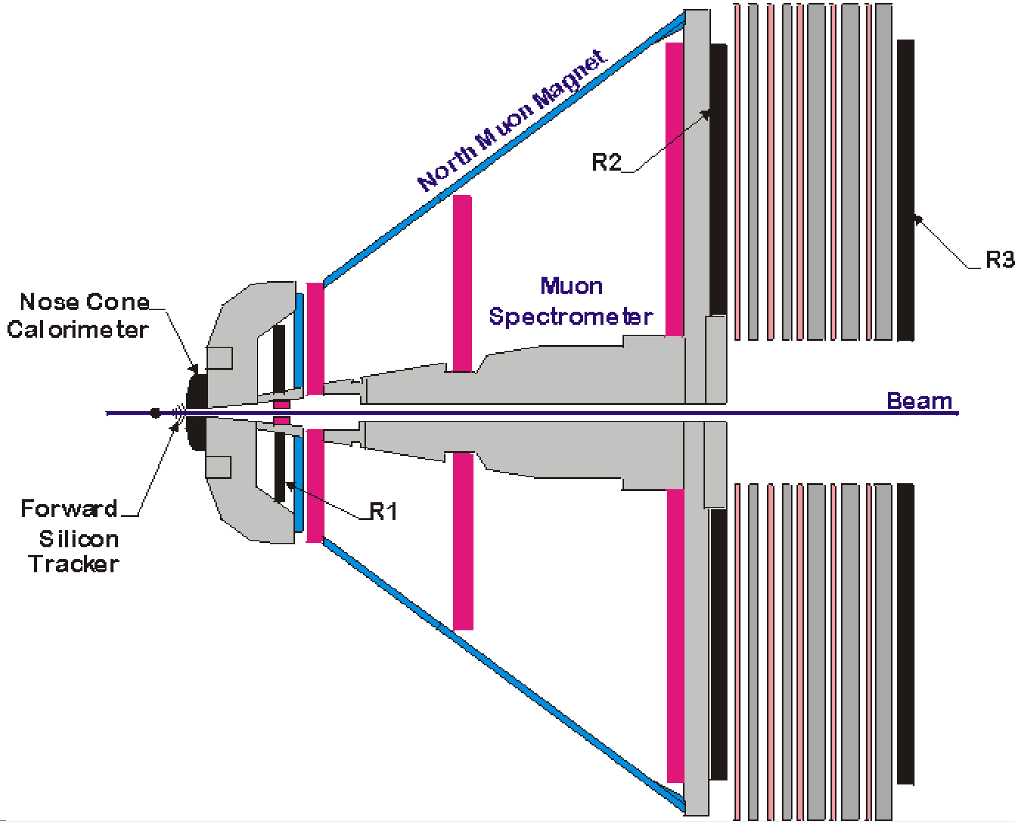


The Future of PHENIX

- Hadron Blind Detector: low mass electron pairs
- Silicon Vertex Detector: mid and forward rapidity HQ, separation of b/c, direct open charm
- Aerogel and RPC TOF: PID to higher P_T
- Nosecone Calorimeter : forward rapidity photons, π^0
- Forward Muon Trigger: high P_T trigger







Conclusions

- Significant flow is observed for all particles, flow scales with eccentricity and n_q: the matter is thermalized and partonic

- Hadrons are strongly suppressed up to 20 GeV/c
  Not an initial state effect. Suppression at partonic level.
  The matter is dense, strongly coupled, and partonic

- Jets are modified and split: the matter is dense

- Direct photons are abundantly produced; an indication of thermal photons at intermediate P_T : the matter is hot

- Charm is suppressed, charm flows: the matter is dense and strongly coupled

- J/ψ are suppressed, magnitude of suppression can be explained by recombination, but other explanations possible: the matter is dense

See talks by Vale, da Silva, and Enokizono for more details

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13 Countries; 62 Institutions; 550 Participants*

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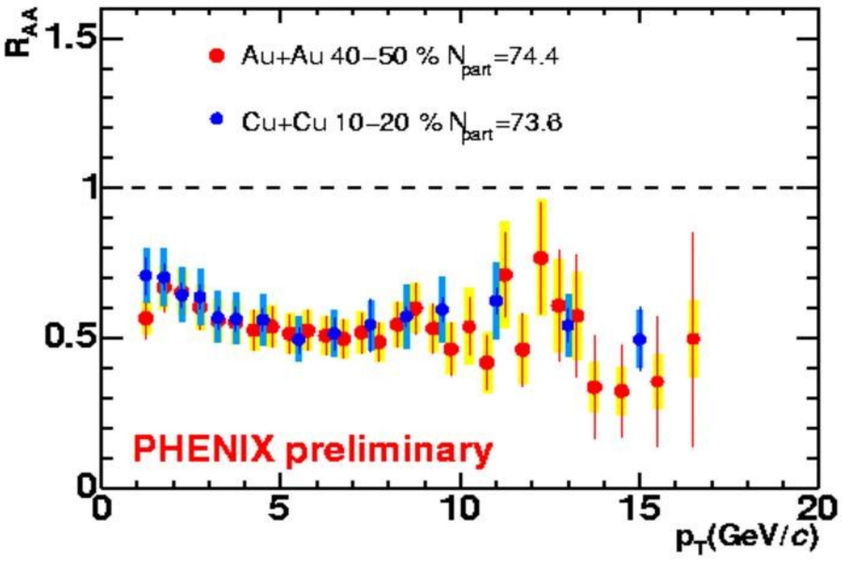
*as of March 2005

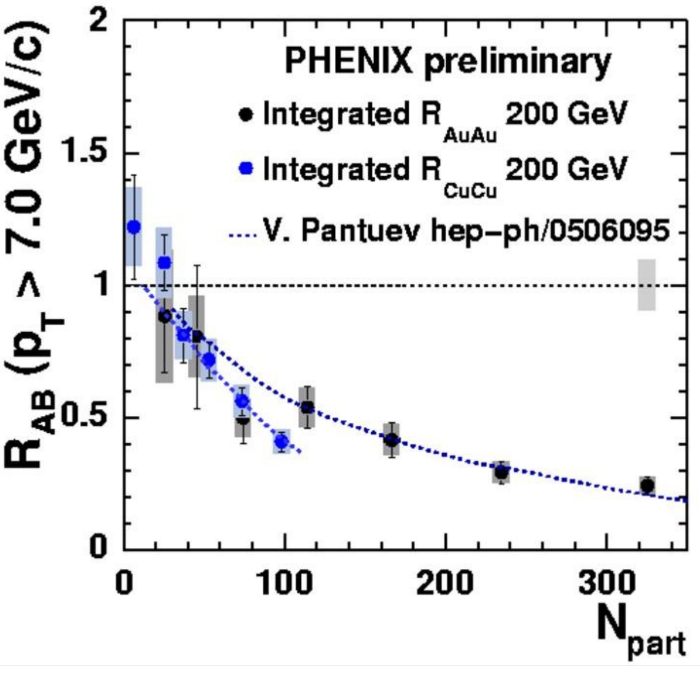
BACKUP SLIDES

Jet quenching vs centrality and system size



Suppression is the same for centrality bins with the same N_{PART}

Energy loss is dominant effect



Integrated R_{AA}:
- qualitatively the same N_{PART} dependence
- quantitative difference due to surface effects

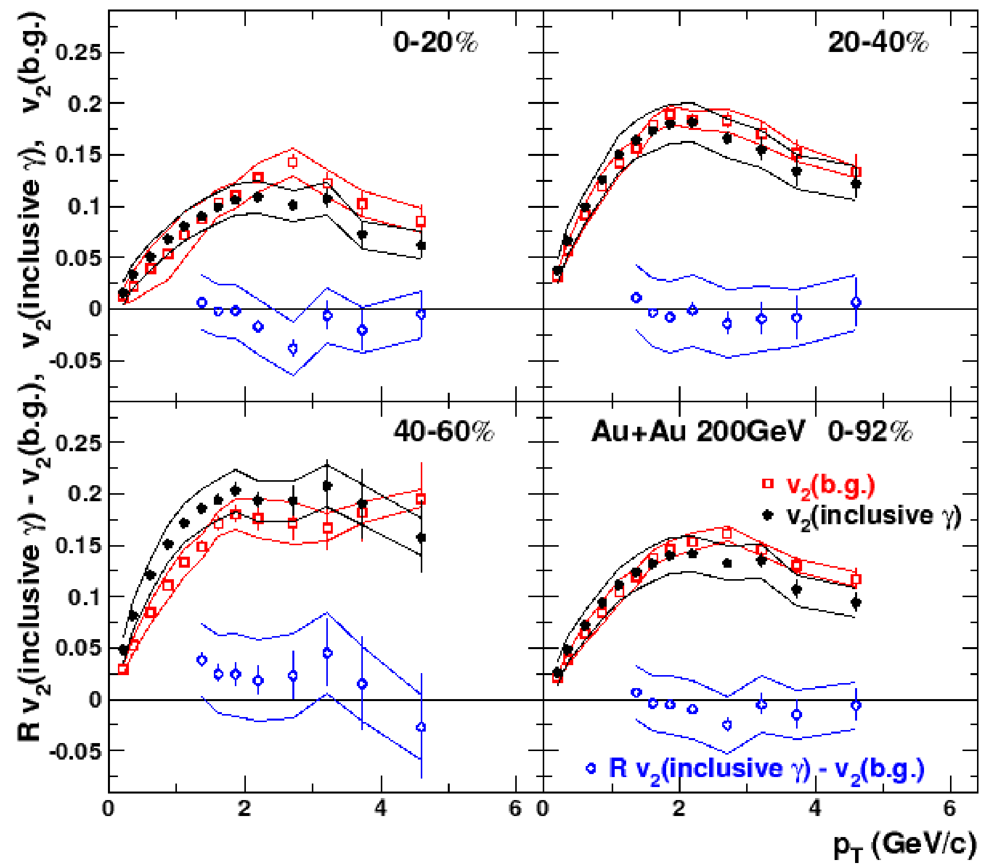
See talk by Carla Vale

Direct Photon Flow

Depending on direct photon source, v_2 should be:

- jet-photon conversion, bremstrahlung: negative
- jet-fragmentation: positive
- thermal: positive
- pQCD: zero

Identified p0 → red
inclusive photons → black
photons → blue



Standard reaction plane method

$$v_2^{direct} = \frac{R \cdot v_2^{inclusive} - v_2^{hadronic}}{R - 1}$$

Consistent with v_2=0 for direct photons

Regeneration or sequential screening?

PHENIX suppression looks the same as NA50 at ~10 times collision energy and ~2-3 times gluon density at RHIC

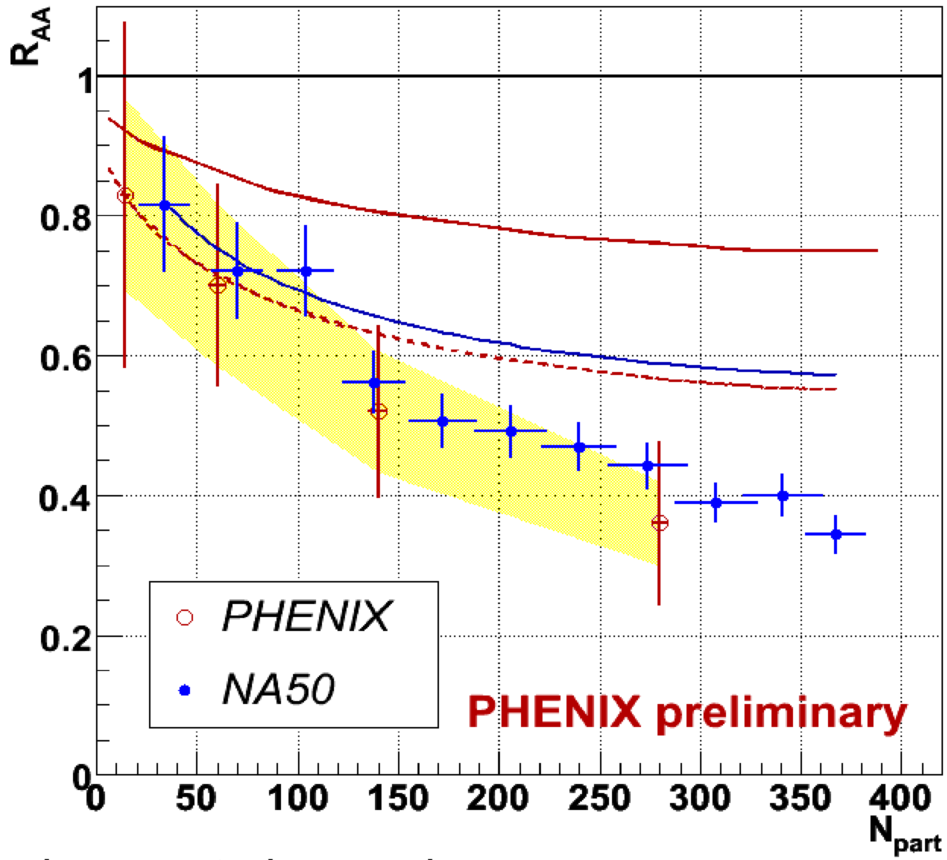
regeneration compensates for stronger suppression?

OR

Sequential screening of the higher mass resonanses down to J/ψ, with J/ψ itself still not dissolved (recent lattice calculations give $T_{J/\psi} > 2T_C$)

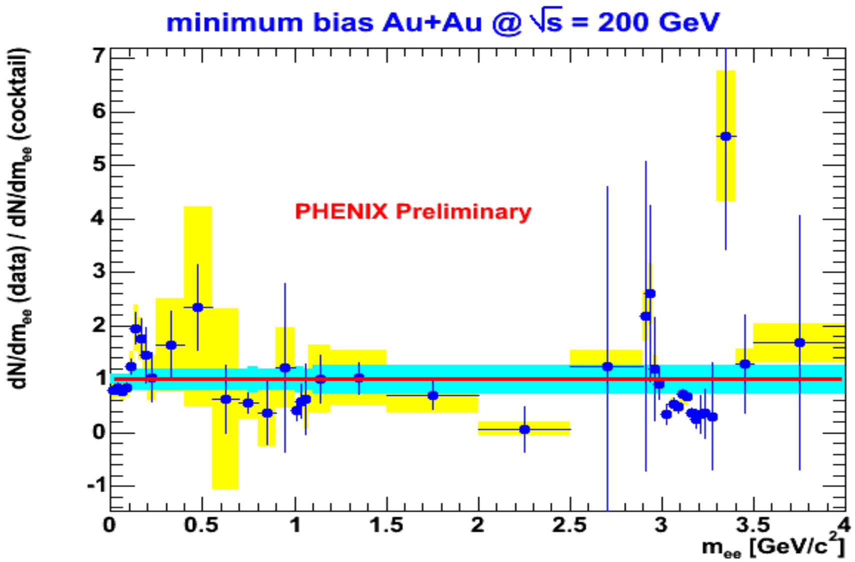
Karsch, Kharzeev, Satz, Phys. Lett. B637:75

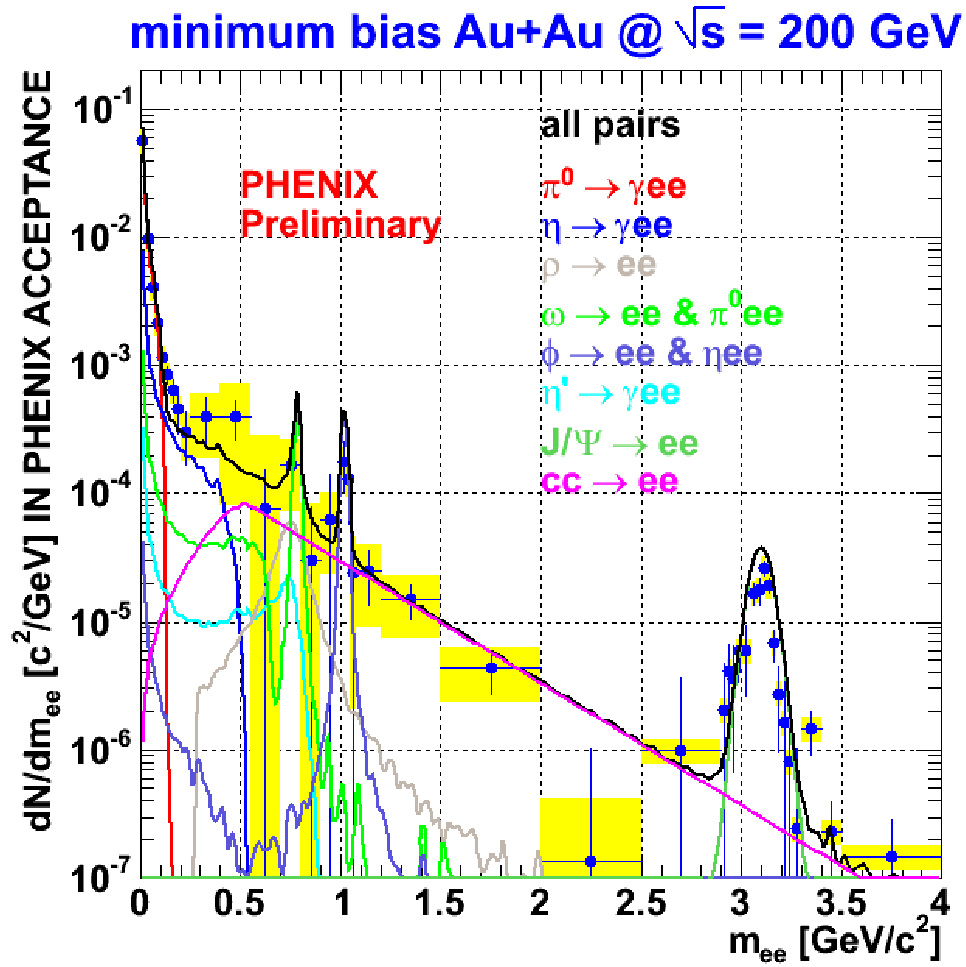
Theory curves below: cold matter effects
R.Vogt, nucl-th/0507027
solid red: shadowing + absorption σ_{abs} = 1mb
dashed red: shadowing + absorption σ_{abs} = 3mb
blue: simple absorption σ_{abs} = 4mb



Regeneration should result in rapidity narrowing – not observed
J/ψ flow? If regeneration dominates J/ψ should inherit flow from charm quarks

Dielectrons



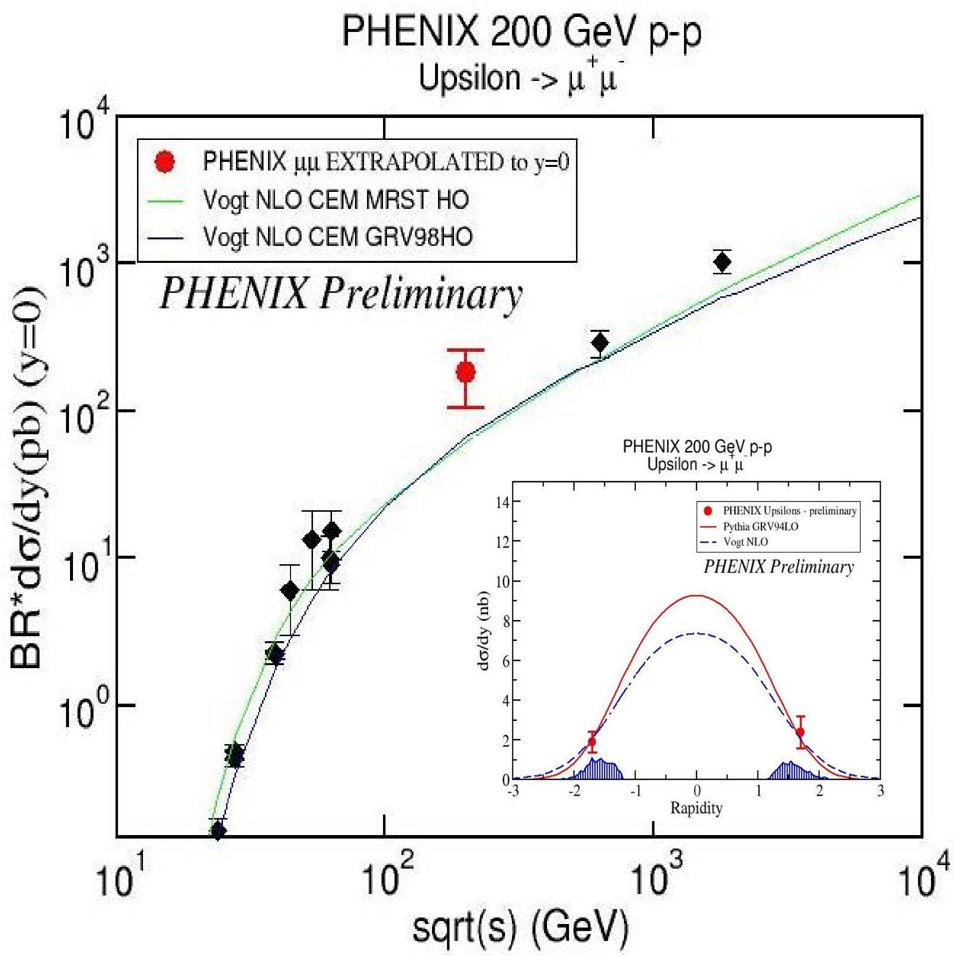


No enhancement above what is expected from decays

Consistent with theoretical calculations, including chiral symmetry restoration

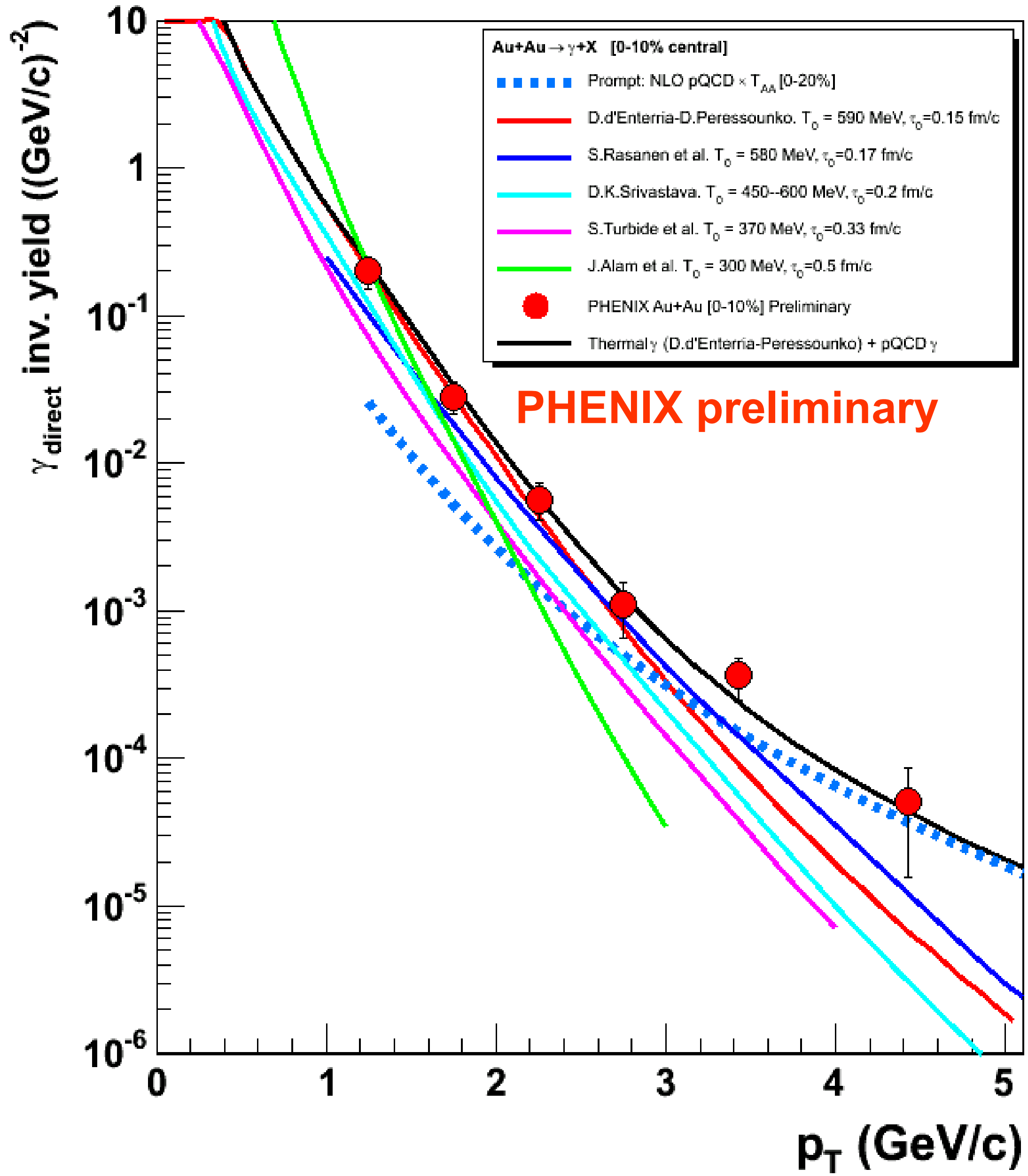
Large systematic errors
HBD upgrade

Upsilons



1st Upsilons at RHIC from ~3pb^{-1} collected during the 2005 run.

Thermal Photons?



The first promising result of direct photon measurement at low PT from conversion pair analysis

The rate is above pQCD calculations

If these photons are indeed thermal, they can provide the first direct measurement of initial temperature of the matter.

Alternative explanations:

Sequential screening of the higher mass resonanses down to J/ψ, with J/ψ itself still not dissolved (recent lattice calculations give $T_{J/\psi}>2T_C$)

Karsch, Kharzeev, Satz, Phys. Lett. B637:75